High Temperature, High AN2 Last Stage Blade for 65% Efficiency

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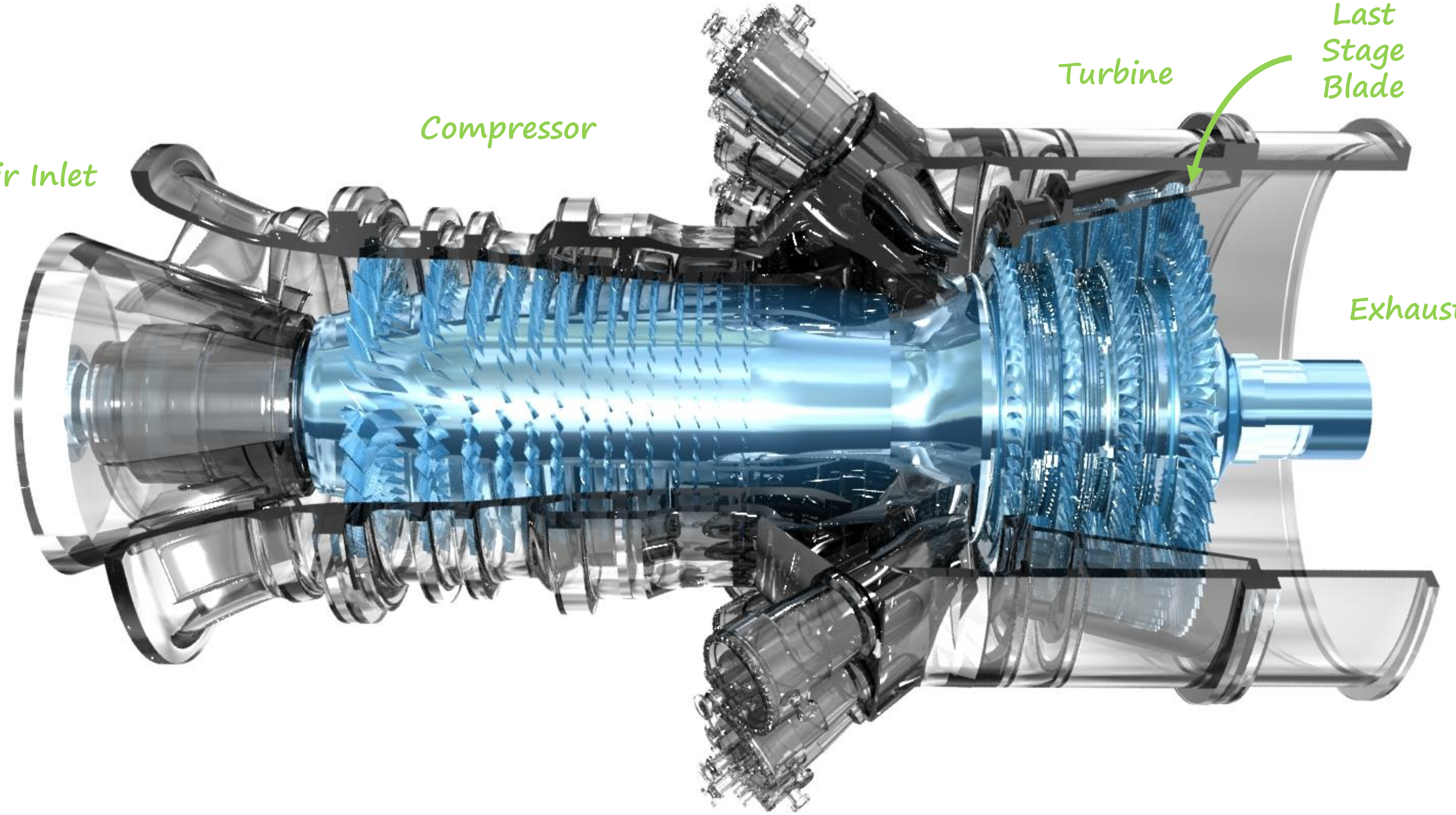
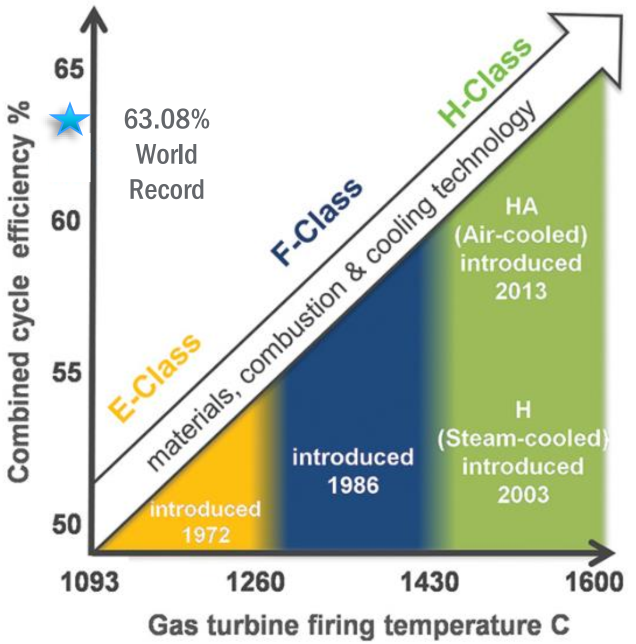
Agenda

- What's a Last Stage Blade
- What's AN^2
- Project Overview
- Task 2 Overview
- Task 3 Overview

What’s a Last Stage Blade?

Industrial Gas Turbine





HA class turbine blades seeing higher flow-path temperatures

Basic Design Attributes

Energy Extraction

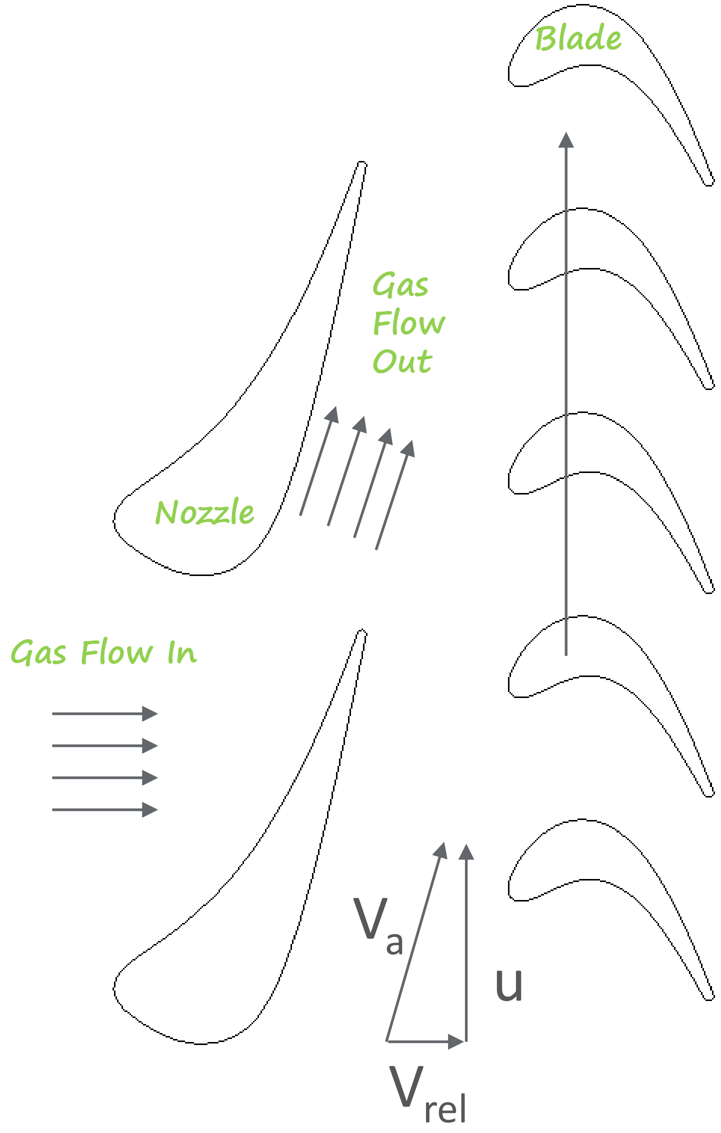
Convert the high temperature, pressure and velocity combustion flow from the upstream nozzle into rotational energy

Mounting

Blades are typically cantilevered from the wheel attachment. Large blades may employ interconnecting shrouds to improve structural rigidity.

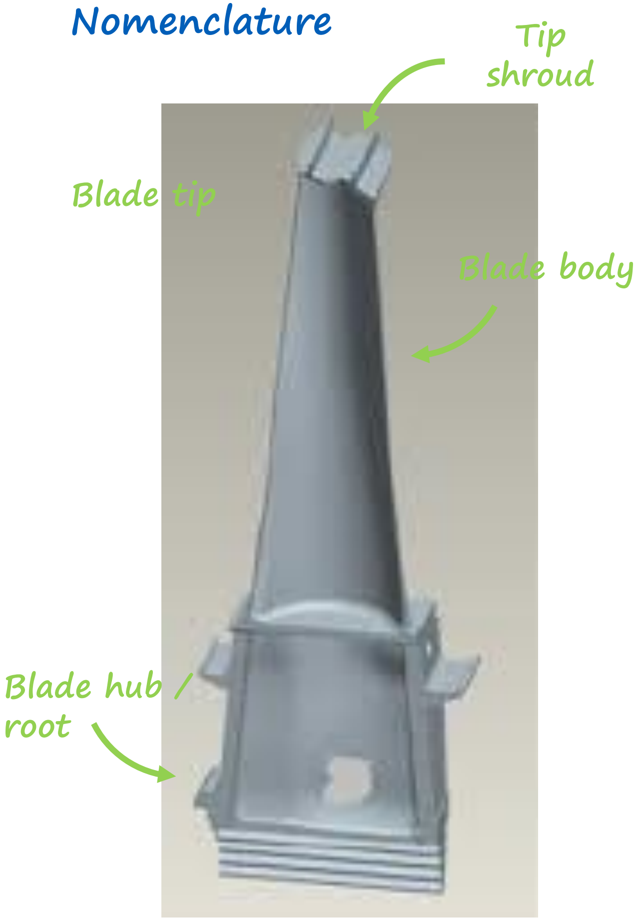
Cooling

- Cooling the blade structure to acceptable bulk temperatures
- More cooling directly reduces engine performance.

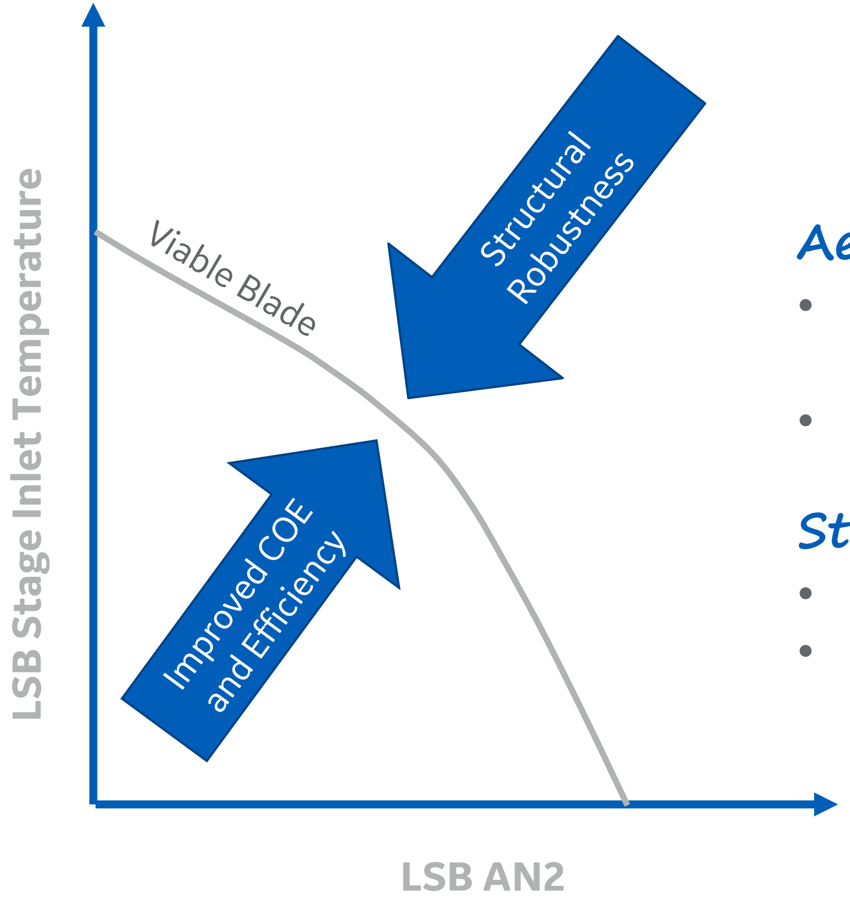


Nomenclature and Challenge

Nomenclature



LSB – Last Stage Blade



COE – Cost of Electricity

Aeromechanics

- Natural mode response, 1F, 1T…
- Aeroelastic instability

Structural Quality

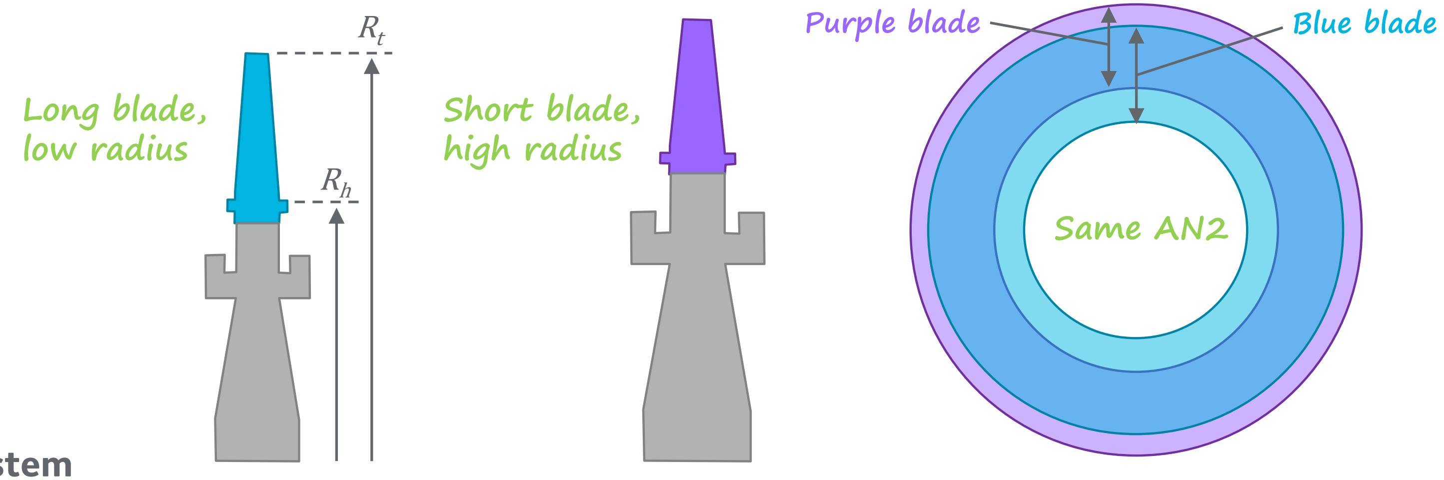
- Low Cycle Fatigue
- Creep

What's a AN^2?

What's AN²?

The AN2 of a rotating turbine blade is a term that the industry uses to characterize blade size and flow capability. It is proportional to the annulus area multiplied by the rotational speed squared:

$$AN2 = \frac{\pi\left(R_t^2 - R_h^2\right)RPM^2}{1 \times 10^9}$$



It is an indicator of:

- **The maximum air flow capability of the turbine system**
  - Airflow is directly correlated with total combined cycle plant output. In general, the larger the AN2, the larger the power output, and the lower the overall GT $/kw and COE.

- **The aerodynamic efficiency of the turbine system**
  - Larger annulus area reduces Mach no thereby increasing stage & diffuser aerodynamic efficiency

- **The level of mechanical and aeromechanical design challenge. For a given AN2:**
  - Longer blade length (R_t-R_h) will result in lower blade and rotor stresses, but lower blade stiffness / frequencies
  - Shorter blade positioned at a higher radius will have increased stresses, but higher blade stiffness / frequencies

LSB AN2 is a major driver of gas turbine and combined cycle plant economics

Program Overview

Project Objectives & Technical Approach

Objective

Develop blade mechanical damping technology and other vibration management strategies to address inherent challenges related to high AN2 LSB thereby advancing the state-of-the art IGT LSB capability.

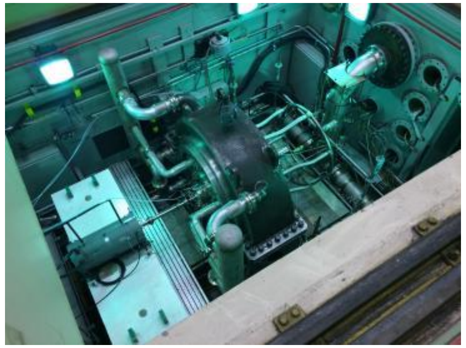
Technical Approach

Phase I - Analytical

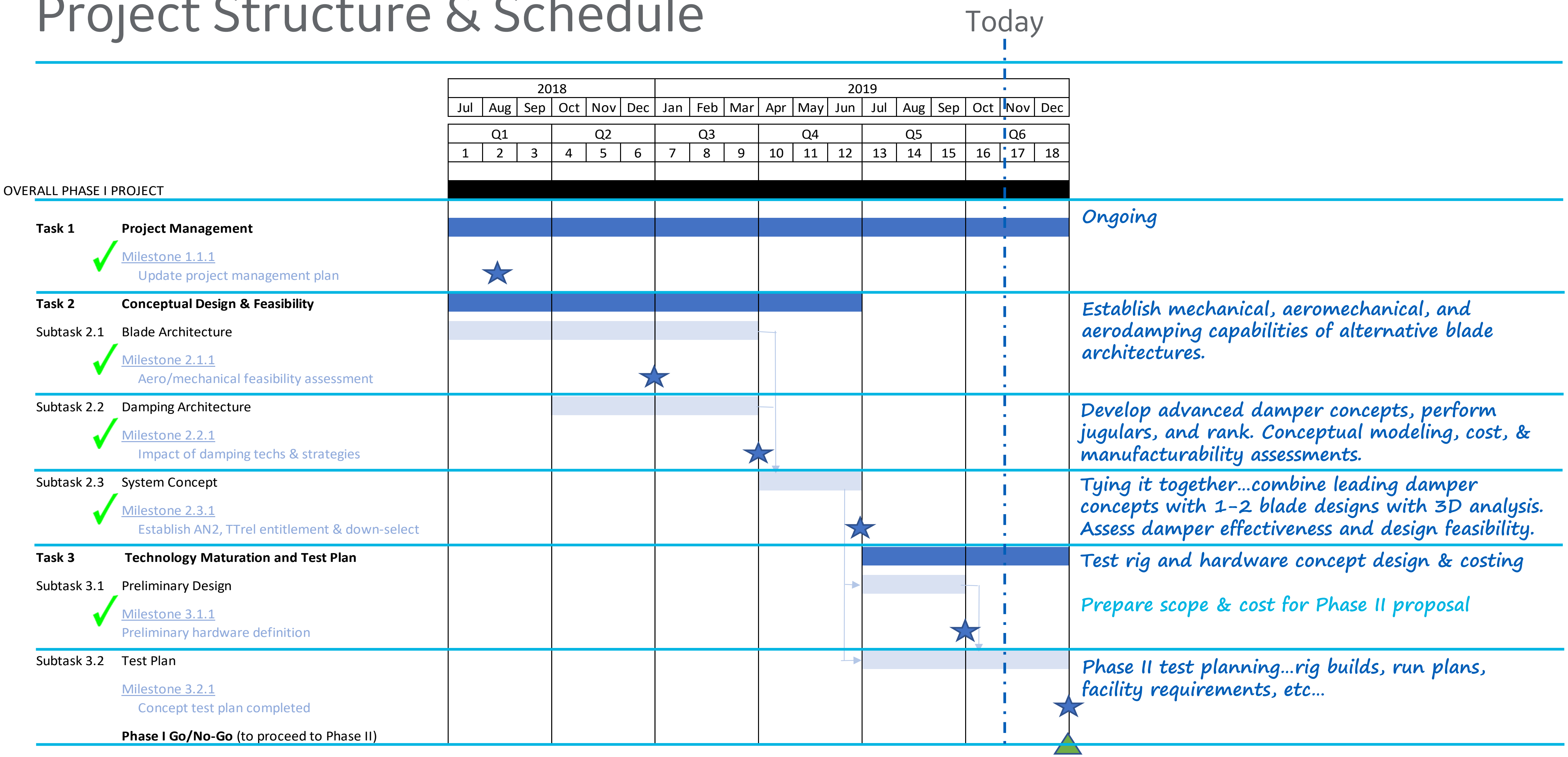
- Develop new damper designs and strategies to maximize damping effectiveness
- Improve understanding of non-synchronous vibration and mitigation strategies
- Perform system trades…cooling requirements, aero efficiency, exit Ma, cost, etc.
- Down-select viable blade-damper solutions on effectiveness, durability, manufacturability, etc.
- Develop Phase II test plans

Phase II – Test & Learn

- Wheelbox testing
- Damper wear
- Manufacturing trials
- Etc…



Project Structure & Schedule



Project Risk Management

Risk Description	Type of risk	Likelihood	Impact	Risk Management (mitigation and response strategies)
LSB blade-rotor system unable to mechanically achieve >=Target AN2 and TTrel	Technical	Low	Medium	Investigate impact of weight reduction strategies (shroud elimination / reduction, higher strength materials, cooling, hollow cavities, etc.)
LSB blade-rotor system unable to aeromechanically achieve >= Target AN2 and TTrel	Technical	Medium	Medium	Investigate impact of designs and technologies that result in increased stiffness and damping effectiveness (count optimization, core, Tm/C, mistuning, novel damping concepts, etc.).
Design elements necessary for Target AN2 and Ttrel result in a loss of turbine performance	Technical	Low	Low	Understand performance degradation contributions of blade design elements (cooling requirements, clearances, etc.) and trade against benefits from AN2 & TIT/Ttrel
Damper solution(s) do not satisfy HCF design requirements (damper effectiveness)	Technical	Medium	Medium	Understand damping requirements for various blade architectures and eliminate non viable options. Validate in Phase II testing.
Damper solution(s) are not robust to high vibration levels or HD GT duty cycle (damper wear)	Technical	Medium	Medium	Leverage current understanding of wear couples. Validate in Phase II testing.
Fidelity of conceptual analysis cannot accurately predict SV & NSV phenomena	Technical	Medium	Medium	Understand and report prediction uncertainty in concept screening (Task 2.0). Improve tools or approach if needed. Confirm design predictions with higher fidelity analysis in Task 3.0.
Availability of team members and experts to complete program milestones	Schedule	Low	Low	Phase I scope is small for an 18 month program schedule. GE to manage the team resources across all engineering demands to insure the DOE milestone obligations are met.

Technical risks are manageable through analytical work, concept ranking, design trades, and Phase II testing.

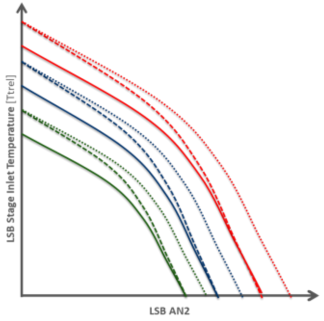
Task 2 Overview

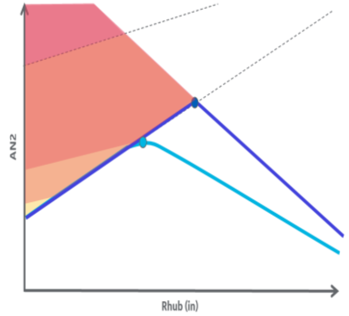
Blade Architecture Studies

Blade & Rotor Mechanical

"How big can I go?"

- 1D blade sizing…section stress analysis vs. design requirements
- Cooling requirements
- Space sweeping design-of-experiments
- 1D wheel sizing, application of system & manufacturing constraints

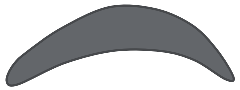


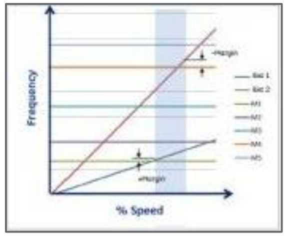


Aeromechanics

"Does frequency avoidance limit my design space? What are the mode shapes?"

- 3D blade design…CFD and FEA analysis
- Modal frequency and modal shape prediction. Margin to design reqt's.
- Design trades…shroud location, count optimization, core, Tm/C, etc.





Aeroelasticity

- Establish stability & margin of design options to non-synchronous vibration
- Understand impact of mistuning

"Is the blade susceptible to flutter or rotating stall?"

Mechanical, aeromechanical, and aerodamping characteristics establish blade damping requirements.

System Studies

Blade-Damper solutions

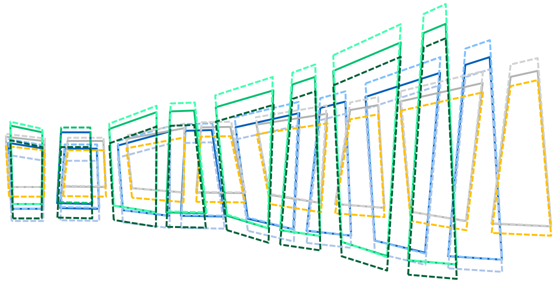
- Combine leading damper concepts with 1-2 blade designs with 3D analysis
- Down-select viable blade-damper solutions
  - effectiveness,
  - durability,
  - manufacturability, etc.

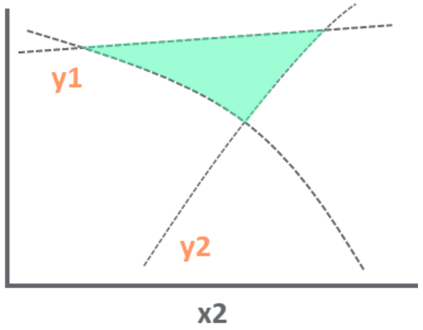
"Can we meet our design objectives and requirement?"

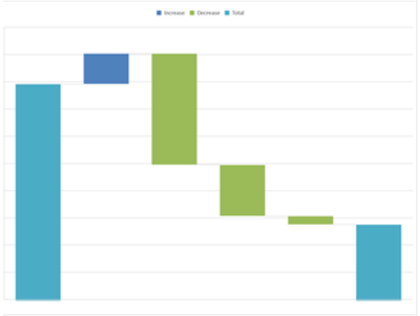
Blade Architecture Trades

- Perform system trades…
  - cooling requirements,
  - aero efficiency,
  - exit Ma,
  - manufacturability,
  - cost, etc.

"What's the best approach for a large, hot LSB?"







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Identify viable design concepts that maximize gas turbine and combined cycle plant economics.

Blade and System Architecture Study Results

DPS: Dual Part-Span shroud
PSO: Part-Span shroud Only
US: Un-Shrouded
RSD: Radial Stem Drilled cooling

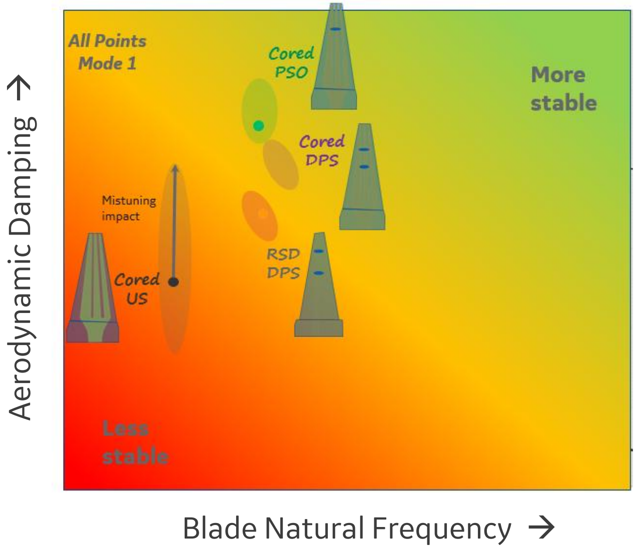
Blade architecture	Mechanical AN2/MW	Campbell	Mech Damping	Aero-Damping	Performance	Rotor Size	Cost	Schedule
RSD DPS								
Cored DPS								
Cored PSO							+	+
Cored US							++	+

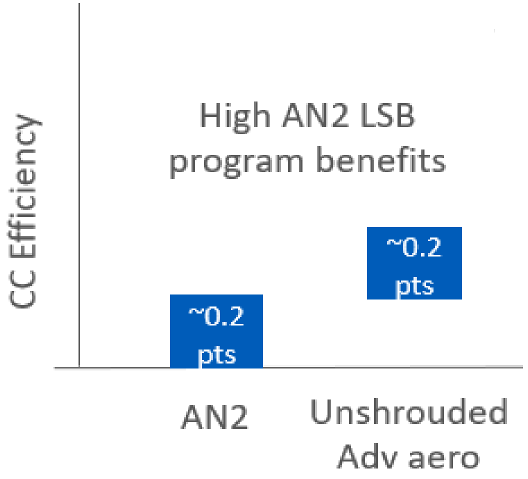
Next Gen LSB

- PSO shroud
- Platform damper
- Novel damper
- Cooled blade

And Beyond…

- US Blade
- Enhanced damping
- Mistuning
- Potential S3B application





Damping Architecture Studies

Concept Identification & IP Mapping

- Identify viable design concepts that improve mechanical damping capability of shrouded and shroudless blade designs
- Understand novelty and intellectual property coverage

"What is the concept? Is it novel or free to practice?"

Concept Development & Design

- Jugular analysis using advanced FEA methods
- Identification of relevant design parameters
- Ranking & down-select on multiple criteria… Q reduction, weight, cost, etc.

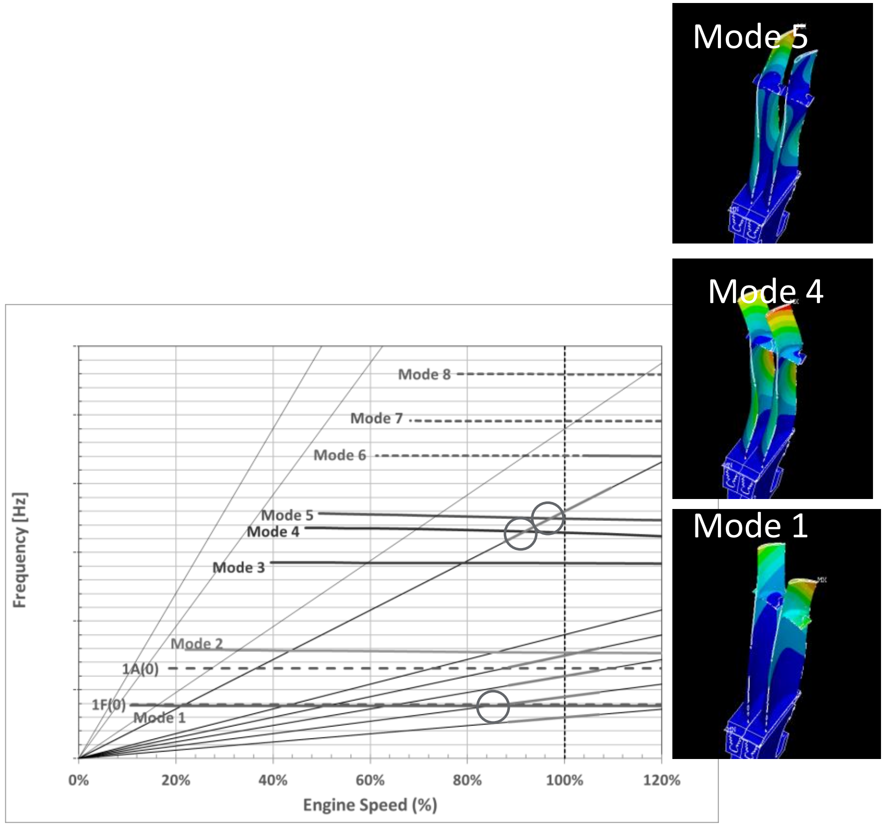
"How capable is the concept and what are the important design parameters?"

Development of novel damping concepts is essential to LSB temperature & AN2 growth

What is Q

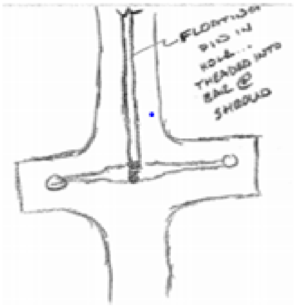
Fundamentals

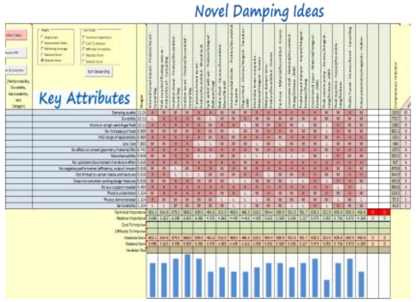
- Damping dissipates energy
- Undamped system response is unbounded at resonance
- Damping bounds the response
- Q is the ratio of the dynamic response at resonance to the static response
- Lower is better.

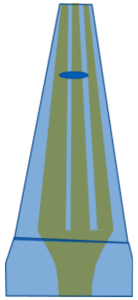


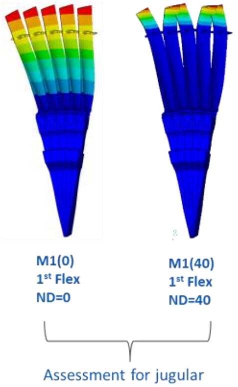
LSB Damping

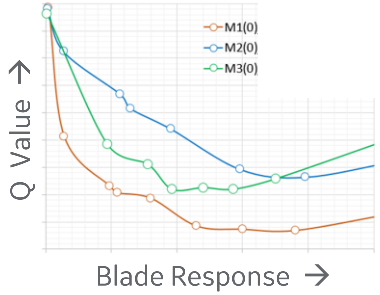
Brainstorm > QFD > Design > Mode Shape > Qcal > Q Compare > Rank



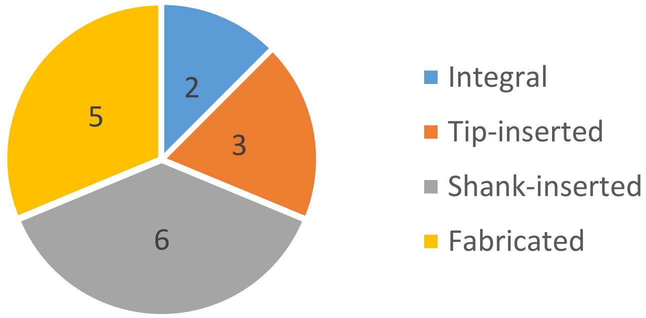


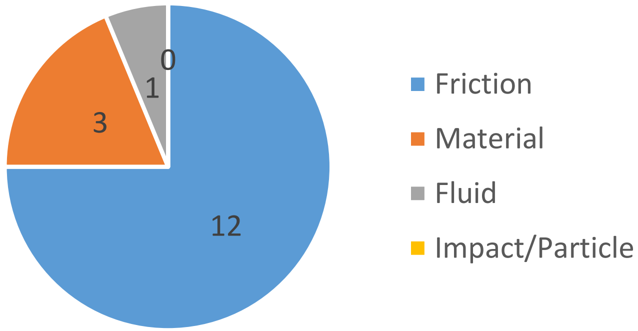






Active in Patent Domain





Fundamentals

- Over 20 ideas
- 2 are shroud dependent
- 1 adds no weight
- 1 not amplitude dependent
- 5 with Q<50

Technology Groups

- Friction (7)
- Material (1)
- Fluid (1)
- Impact (1)

Application Groups

- Integral (2)
- Inserted (4)
- Fabricated (4)

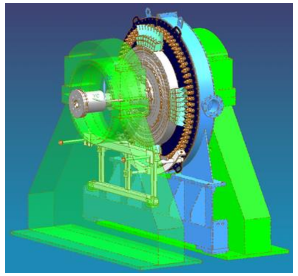
Task 3 Overview

Technology Maturation and Test Plan

Objective of plan

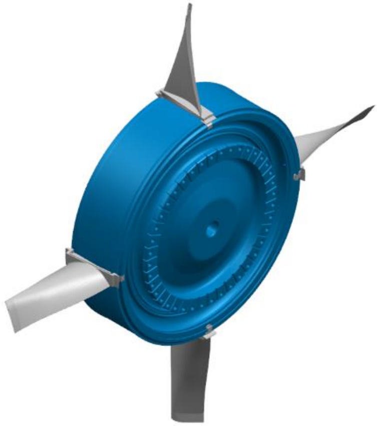
Determine approach to validate blade mechanical damping technology and other vibration management strategies to advance the state-of-the art IGT LSB capability

Approach



Build, Test & Learn
- Damper Design
- Integrating with Blade
- Manufacturing Trials
- Damper Durability Test
- Wheelbox Test

Key Deliverables
- Successful damper definition
- Blade damper demonstration
- Damping tech curves



Hardware
- Blades
- Dampers
- Rotor
- Excitation manifold
- Plumbing
- Slipring and DAC
- Light probes, mounts and DAC
- Wheel-box expendables
- Test Equip Cals

Test
- Design/Fab/Install/Test/Teardown
- Blade/damper builds (different dampers)
- Speed sweeps
- Excitation nozzle arrangements
- Various excitation strengths
- Instrumentation hookup and measurement (SGs, TCs, light probes)

Q&A
Discussion